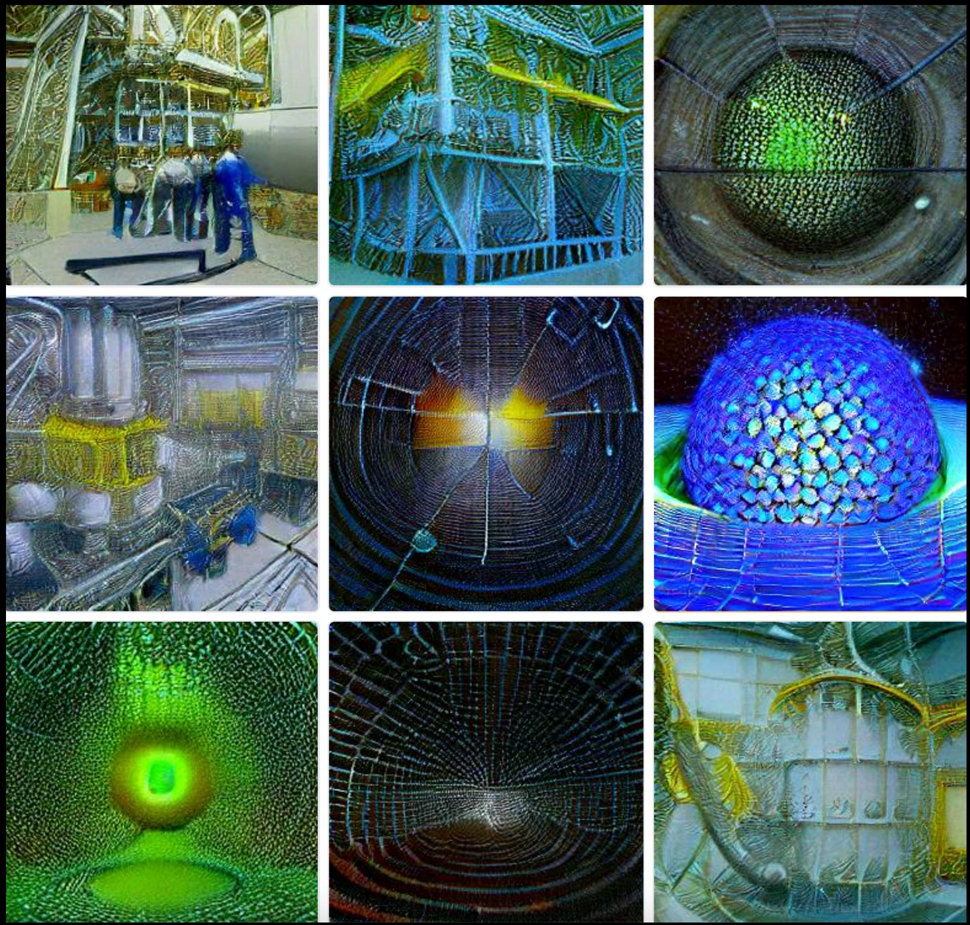
Snowmass Neutrino Frontier Summary



Kate Scholberg, Duke University

NF co-conveners: Patrick Huber, Elizabeth Worcester

P5 Town Hall, March 21, 2023

*DALL-E-mini output for "searching for beyond the standard model physics in the neutrino sector at the neutrino frontier"

Outline

Snowmass Neutrino Frontier
The ~3 year process

Physics Content
What are the big questions in the NF?
What's the status of answering them?
What do we still need to know?

Messages from the NF Community
The summary output of Snowmass

Project Summary
Coarse timescale and cost

Neutrino Physics Frontier

Co-Conveners

Patrick Huber
Virginia Tech

Kate Scholberg
Duke University

Elizabeth Worcester
BNL

Topical Groups and Co-Conveners (many overlaps)

Topical Group	Co-Conveners			
NF01: Neutrino Oscillations	Peter Denton	Megan Friend	Mark Messier	Hiro Tanaka
NF02: Anomalies	Georgia Karagiorgi	Bryce Littlejohn	Pedro Machado	Alex Sousa
NF03: Beyond the SM	Pilar Coloma	Lisa Koerner	Ian Shoemaker	Jae Yu
NF04: Neutrinos from Natural Sources	Yusuke Koshio	Gabriel Orebi Gann	Erin O'Sullivan	Irene Tamborra
NF05: Neutrino Properties	Carlo Giunti	Lisa Kaufman → Julieta Gruszko	Ben Jones	Diana Parno
NF06: Neutrino Interactions	Baha Balantekin	Jonathan Asaadi → Steven Gardiner	Kendall Mahn	Jason Newby
NV07: Nuclear Safeguards and Other Applications	Nathaniel Bowden	Jon Link	Wei Wang	
NF08/TF11: Theory of Neutrino Physics	André de Gouvêa	Irina Mocioiu	Saori Pastore	Louis Strigari
NF09: Artificial Neutrino Sources	Laura Fields	Alysia Marino	Pedro Ochoa	Josh Spitz
NF10: Neutrino Detectors	Josh Klein	Ana Machado	Dave Schmitz	Raimund Strauss

[redacted]

Neutrino Physics Frontier Liaisons

Frontier	Liaison
Computational Frontier	Alex Himmel
Cosmic Frontier	Tali Figueroa-Feliciano → Kim Palladino, Yvonne Wong
Rare Processes and Precision Frontier	Bob Bernstein
Accelerator Frontier	Laura Fields → Alysia Marino
Energy Frontier	André de Gouvêa
Instrumentation Frontier	Mayly Sanchez
Community Engagement Frontier	Claire Lee
Underground Facilities Frontier	Albert de Roeck
Theory Frontier	K.S. Babu, Irina Mocioiu

And special shout-out to **SEC liaisons**:

Erin Conley, Jay Hyun Jo, Tanaz Mohayai, Vishvas Pandey, Jacob Zettlemoyer, Xianyi Zhang

NF Snowmass Timeline

- Topical groups formed: April 2020
- Neutrino Town Hall: July 2020
- 324 Snowmass Letters of Interest in August 2020
- Topical group workshops in fall 2020
- Snowmass Pause: first half of 2021
- "White paper workshops" through fall of 202
- Series of meetings for community feedback on TG reports : Jan-Mar 2022
- Topical Group Report drafts posted (NF): March 2022
- Community feedback period: March 11-April 10
- NF Workshop @ ORNL: March 16-18 [hybrid]
- **All-Snowmass Community NF Colloquium Series**: March-May
- Preliminary (TG & Frontier) Reports drafts May 2021
- Community feedback period: June 1 – July 26
- Community Summer Study (Seattle): July 17-26
- Final (TG & Frontier) Report drafts and feedback: late summer/fall 2022
- Final NF report posted Nov 2022

well worth your time!

https://snowmass21.org/neutrino/start

Huge, interactive community participation... thank you!

[redacted]

And the Snowmass NF output!

High Energy Physics – Experiment

[Submitted on 16 Nov 2022 (v1), last revised 9 Dec 2022 (this version, v2)]

Snowmass Neutrino Frontier Report

Patrick Huber, Kate Scholberg, Elizabeth Worcester, Jonathan Asaadi, A. Baha Balantekin, Nathaniel Bowden, Pilar Coloma, Peter B. Denton, André de Gouvêa, Laura Fields, Megan Friend, Steven Gardiner, Carlo Giunti, Julieta Gruszko, Benjamin J.P. Jones, Georgia Karagiorgi, Lisa Kaufman, Joshua R. Klein, Lisa W. Koerner, Yusuke Koshio, Jonathan M. Link, Bryce R. Littlejohn, Ana A. Machado, Pedro A.N. Machado, Kendall Mahn, Alysia D. Marino, Mark D. Messier, Irina Mocioiu, Jason Newby, Erin O'Sullivan, Juan Pedro Ochoa-Ricoux, Gabriel D. Orebi Gann, Diana S. Parno, Saori Pastore, David W. Schmitz, Ian M. Shoemaker, Alexandre Sousa, Joshua Spitz, Raimund Strauss, Louis E. Strigari, Irene Tamborra, Hirohisa A. Tanaka, Wei Wang, Jaehoon Yu, K S. Babu, Robert H. Bernstein, Erin Conley, Albert De Roeck, Alexander I. Himmel, Jay Hyun Jo, Claire Lee, Tanaz A. Mohayai, Kim J. Palladino, Vishvas Pandey, Mayly C. Sanchez, Yvonne Y.Y. Wong, Jacob Zettlemoyer, Xianyi Zhang, Andrea Pocar

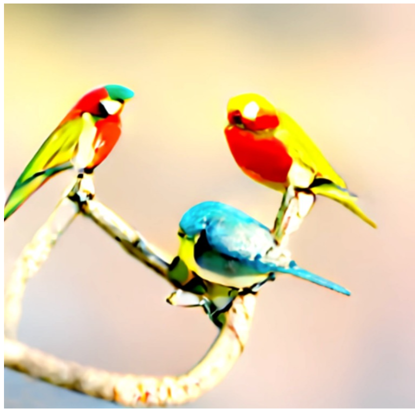
This report summarizes the current status of neutrino physics and the broad and exciting future prospects identified for the Neutrino Frontier as part of the 2021 Snowmass Process.

Comments: 49 pages, contribution to: 2021 Snowmass Summer Study. Minor updates
Subjects: **High Energy Physics – Experiment (hep-ex)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); Solar and Stellar Astrophysics (astro-ph.SR); High Energy Physics – Phenomenology (hep-ph); Nuclear Experiment (nucl-ex)
Cite as: arXiv:2211.08641 **[hep-ex]**
(or arXiv:2211.08641v2 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2211.08641

+ 10 Topical Group reports
+ 87 white papers

Science Drivers in Neutrino Physics

These overlap many of our topical groups



Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

[redacted]

Science Drivers in Neutrino Physics

These overlap many of our topical groups

Three-flavor paradigm: filling in the remaining pieces

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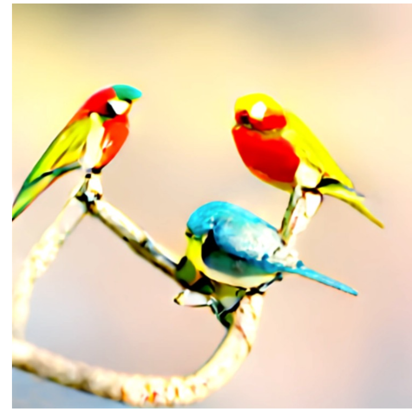
Understanding **astrophysics** and **cosmology**

The three flavor paradigm

what's known,
what's left to measure?



Neutrino Oscillations
Latest 3-flavor results

Remaining unknowns in
the 3-flavor picture:
mass ordering (**MO) and CP** δ

The mass pattern

Absolute Mass
Status and prospects

The mass scale

Majorana vs Dirac?
Overview of NLDBD

The mass nature

[redacted]

The three-flavor neutrino paradigm

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi}|\nu_i\rangle$$

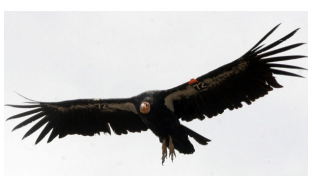
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

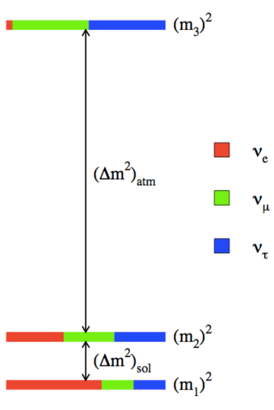
$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

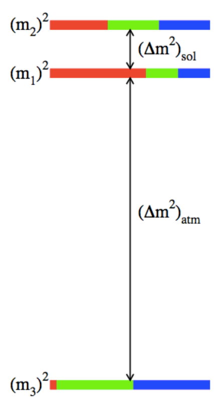
$$s_{ij} \equiv \sin\theta_{ij},\ c_{ij} \equiv \cos\theta_{ij}$$

signs of the mass differences matter

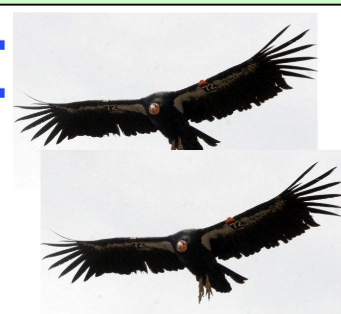




Normal ordering



Inverted ordering



The three-flavor picture fits the data well

Global three-flavor fits to all data: atmospheric, solar, reactor, beams*

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
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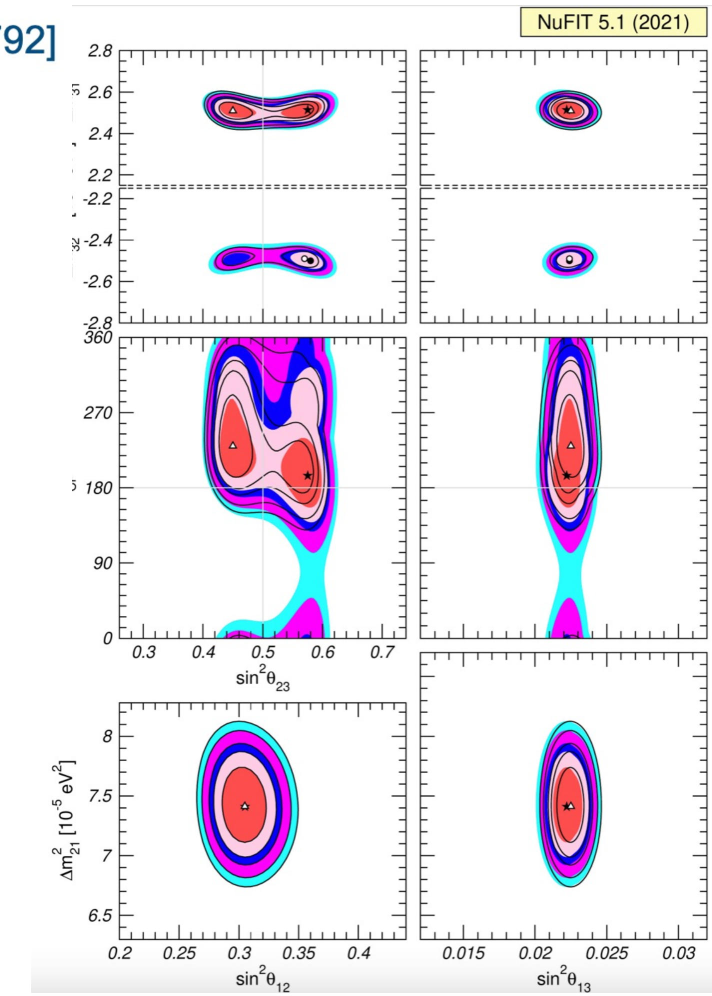
$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

$$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0 \text{ for NO and } \Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0 \text{ for IO.}$$



[redacted]

Esteban et al., arXiv:2007.14792, 10.1007/JHEP09(2020)178

*Does not include the very latest data

What do we *not* know about the three-flavor paradigm?

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

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sign of Δm^2 unknown
(ordering of masses)

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Is θ_{23} non-negligibly greater or smaller than 45 deg?

sign of Δm^2 unknown (ordering of masses)

[redacted]

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poor knowledge*

sign of Δm^2 unknown (ordering of masses)

[redacted]

*CP-conserving values excluded at 90% by T2K

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poor knowledge

sign of Δm^2 unknown (ordering of masses)

More and better info from:
beams [LBL], burns [solar, JUNO], bangs [SNe]...

[redacted]

Where we are now with long-baseline experiments

Past → Current → Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K
J-PARC to Kamioka
295 km, 380-750 kW

[redacted]

And the future...

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K (II)
J-PARC to Kamioka
295 km, 380-750 kW ➔>1 MW

LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2+ MW)

Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)

Current experiments with ~5 yr projections (so, *c*. 2027)

Precision on θ_{12}, θ_{13}, Δm^2_{21}

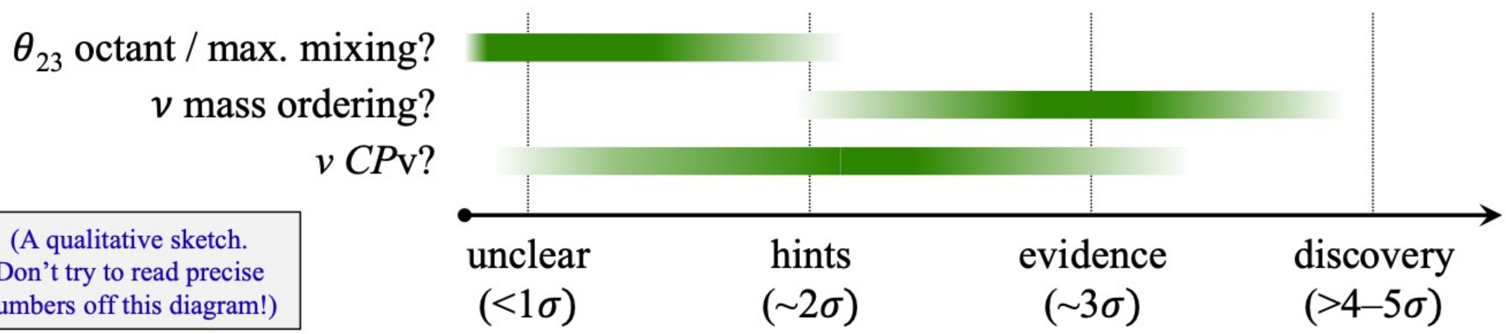
→ Minimal changes until next-gen experiments *(e.g., JUNO)*

Precision on θ_{23}, $|\Delta m^2_{32}|$

→ Some gains to come in current generation. Large gains in next-gen.

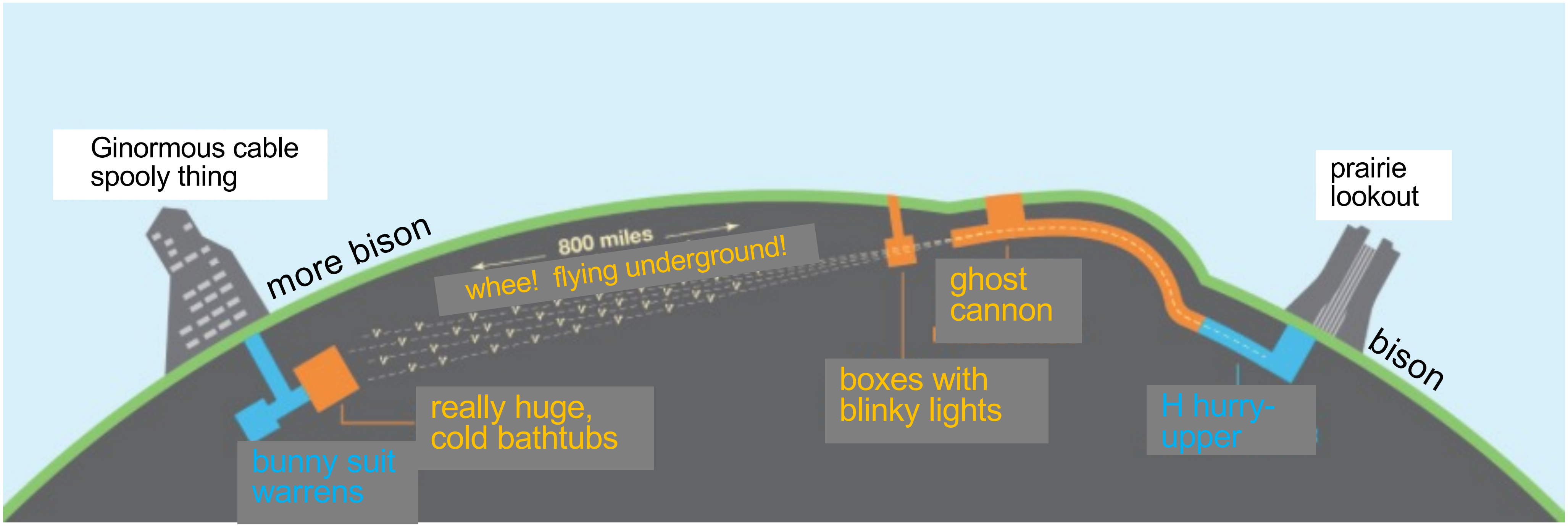
3-flavor "structural" questions

→ Reach heavily depends on (*still unknown!*) actual answers

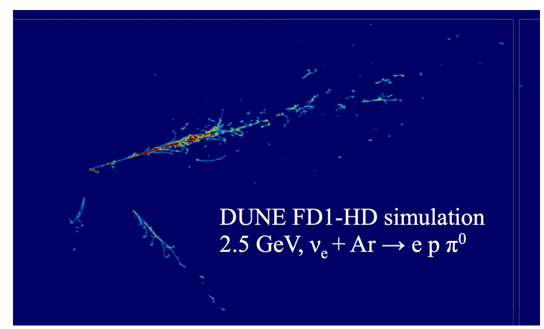


(A qualitative sketch. Don't try to read precise numbers off this diagram!)

Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility



- **Last P5 recommended 4x17kt LArTPC underground, wideband beam, suitable ND, international**
- <u>Phase I</u>: near + far site infrastructure, upgradeable 1.2 MW beam, 2x18 kt LArTPC, movable ND + m catcher, on-axis ND
- <u>Phase II</u>: two more FD modules, >2 MW beam, ND upgrades [new ideas!]
- Broad physics program



Much more info in next talks

Neutrino Oscillations

Latest 3-flavor results

Remaining unknowns in the 3-flavor picture: **MO and CP δ**

Beyond 3-flavor?

Absolute Mass

Status and prospects

Majorana vs Dirac?

Overview of NLDBD

The mass pattern

The mass scale

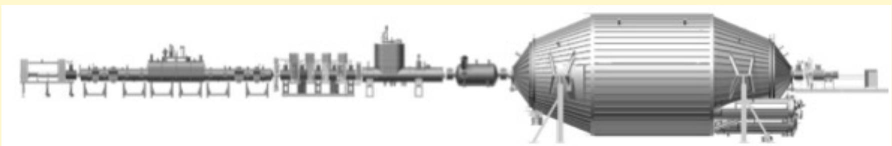
The mass nature

Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

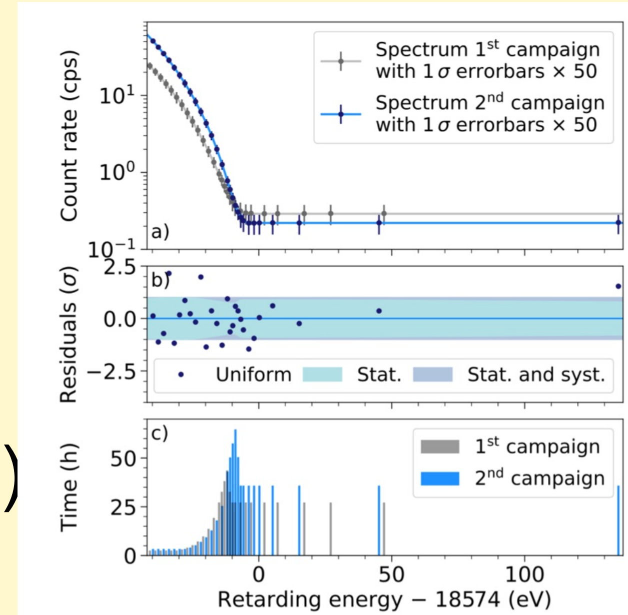
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e}$$

18.6 keV endpoint



Sensitivity to ~0.2 eV (2025)

First results, taking more data



$m_{\nu} < 0.8$ eV (90% CL)

Next data release end of 2023 (<0.5 eV)

Thierry Lasserre Moriond EW 2023

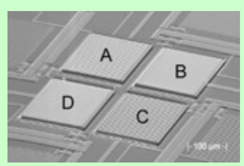
Holmium

e.g., **ECHo, HOLMES**

$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{e}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{C}$$

metallic magnetic calorimeters

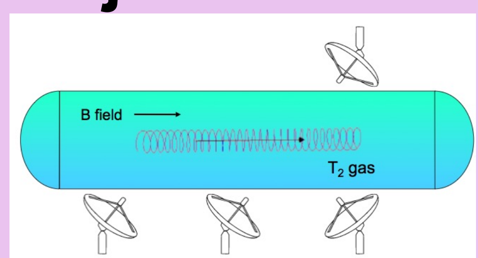


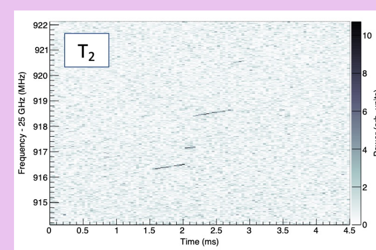
Electron capture decay,
ν mass affects deexcitation spectrum
R&D in progress

R&D

Cyclotron radiation tritium spectrometer: Project 8

R&D, first m_{β} limit





Long-term potential ~40 meV

Neutrino Oscillations

Latest 3-flavor results

Remaining unknowns in the 3-flavor picture: **MO and CP δ**

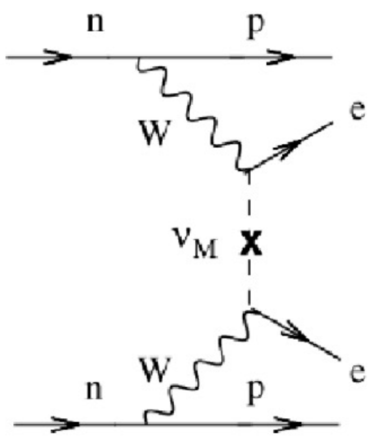
Beyond 3-flavor?

Absolute Mass

Status and prospects

Majorana vs Dirac?

Overview of NLDBD



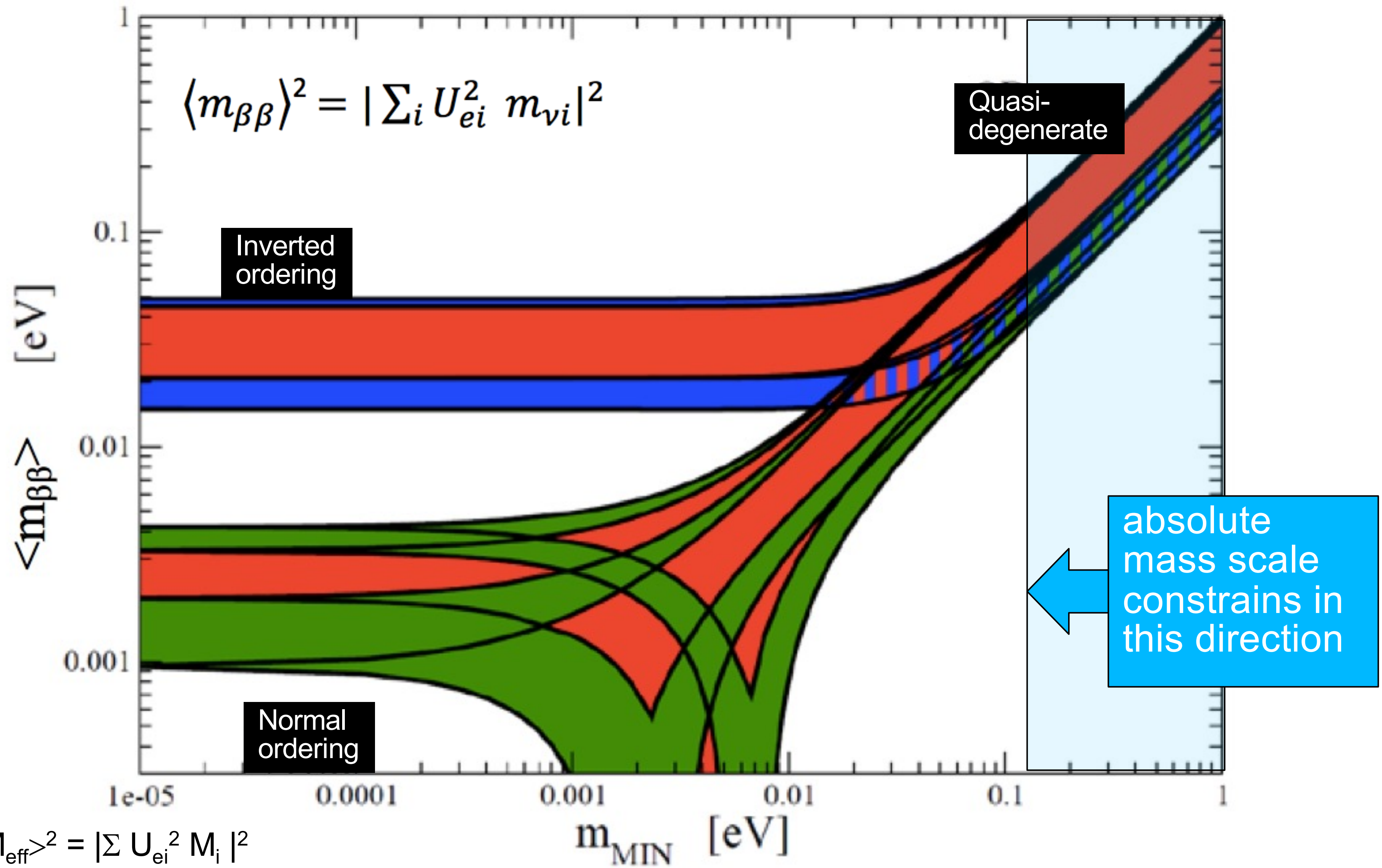
The mass pattern

The mass scale

The mass nature

[redacted]

The NLDBD T-Shirt Plot



$<M_{eff}>^2 = |\Sigma\ U_{ei}^2\ M_i\ |^2$

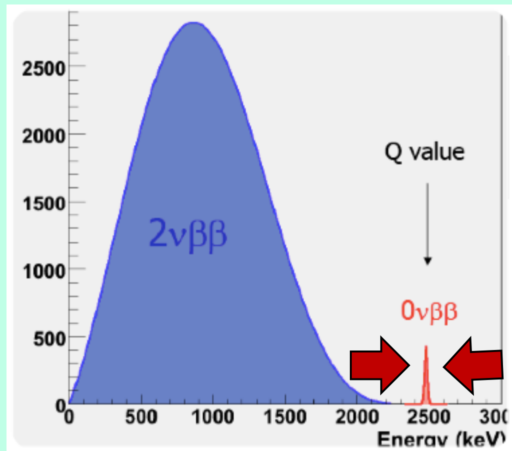
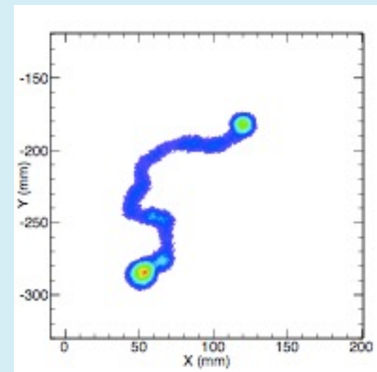
***If* neutrinos are Majorana, experimental results must fall in the shaded regions**

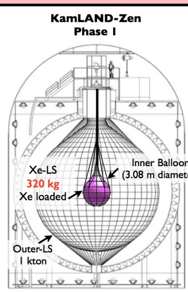
Extent of the regions determined by uncertainties on Majorana phases and mixing matrix elements

[redacted]

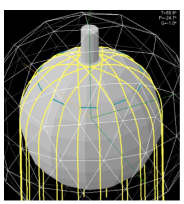
General NLDBD experiment strategies

$$T_{1/2} > \frac{\ln 2\ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

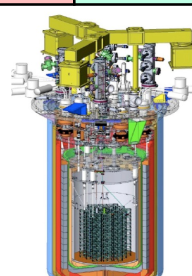
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		



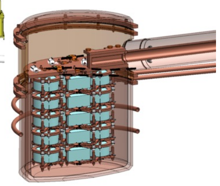
KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)

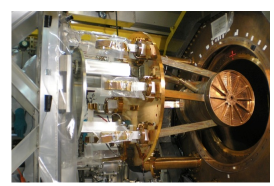


CUORICINO/ CUORE (^{130}Te)

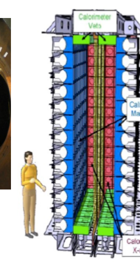


MAJORANA (^{76}Ge)

GERDA (^{76}Ge)



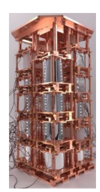
EXO (^{136}Xe)



NEMO/ SuperNEMO (various/^{82}Se)

CUPID (^{82}Se)

CUPID -Mo (^{100}Mo)



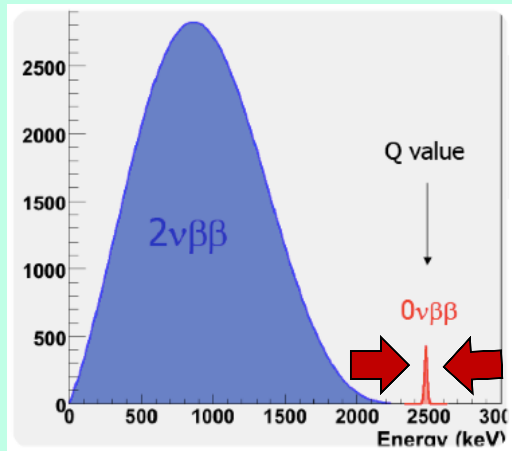
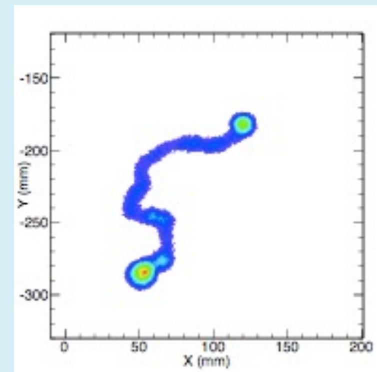
AMORE (^{100}Mo)

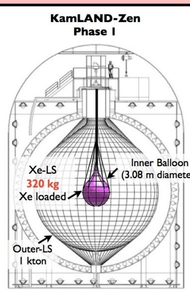
[redacted]

General NLDBD experiment strategies

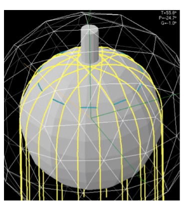
$$T_{1/2} > \frac{\ln 2\ \varepsilon \cdot \boxed{N_{source}} \cdot T}{UL\left(\boxed{B(T)} \cdot \boxed{\Delta E}\right)}$$

US Ton Scale Program

The “Brute Force” Approach	The “Peak-Squeezer” Approach	The “Final-State Judgement” Approach
		

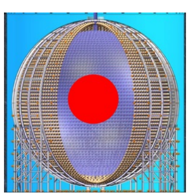


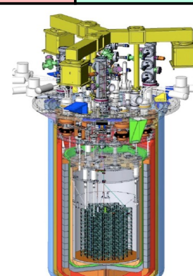
KamLAND-Zen (^{136}Xe)



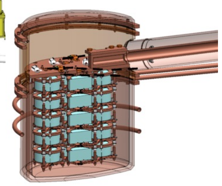
SNO+ (^{130}Te)

JUNO-ββ (^{136}Xe, ^{130}Te)





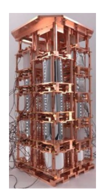
CUORICINO/ CUORE (^{130}Te)



MAJORANA (^{76}Ge)

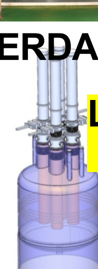
CUPID (^{82}Se)

CUPID -Mo (^{100}Mo)

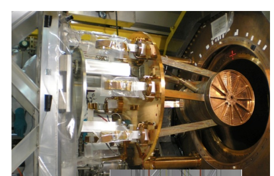


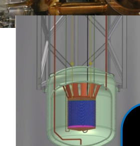
AMORE (^{100}Mo)

GERDA (^{76}Ge)



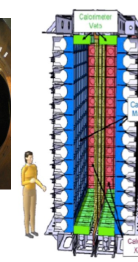
LEGEND (^{76}Ge)



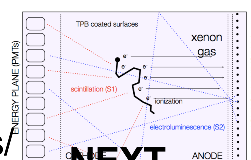


nEXO (^{136}Xe)

+more...

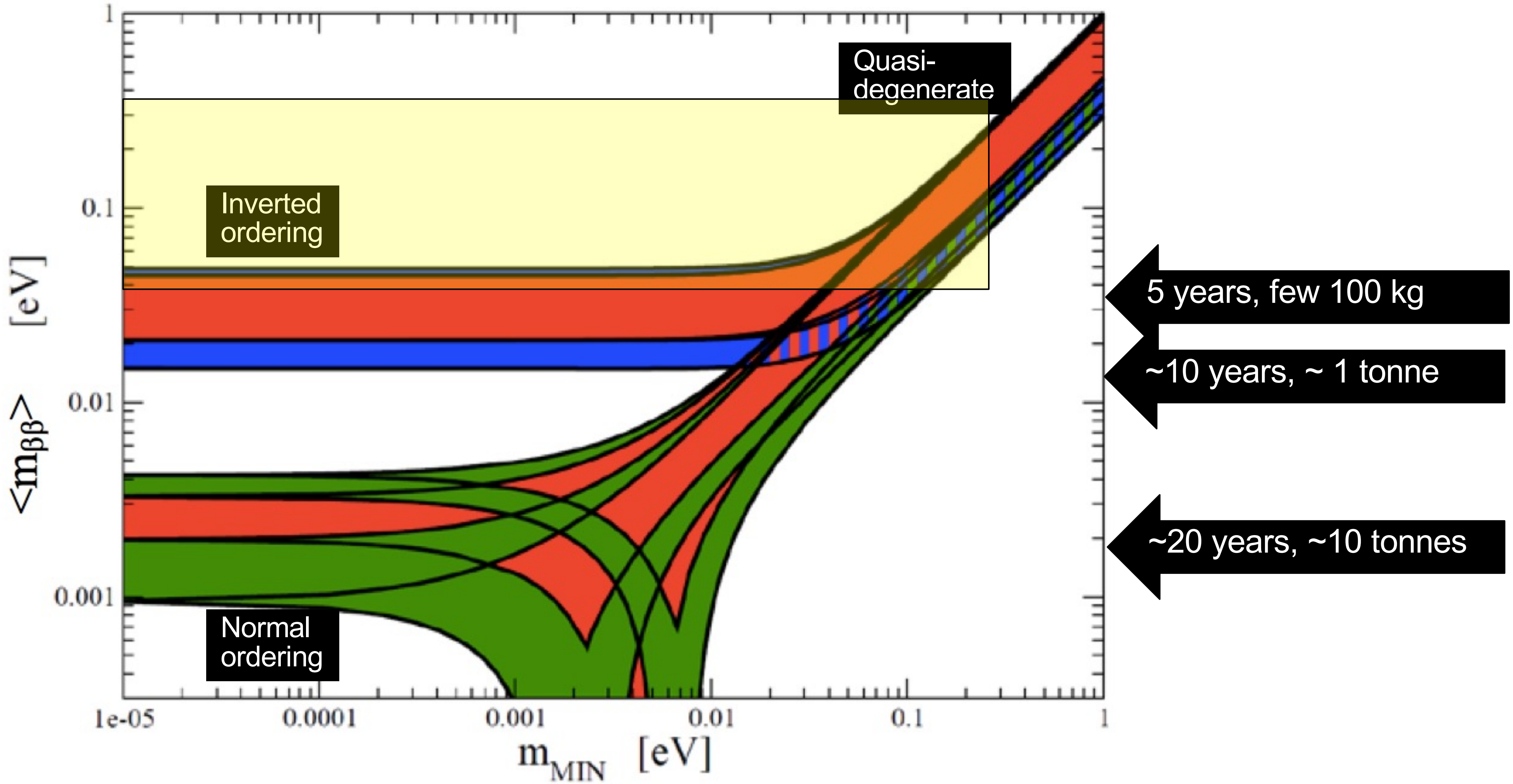


NEMO/ Super NEMO (various/ ^{82}Se)



NEXT (^{136}Xe)

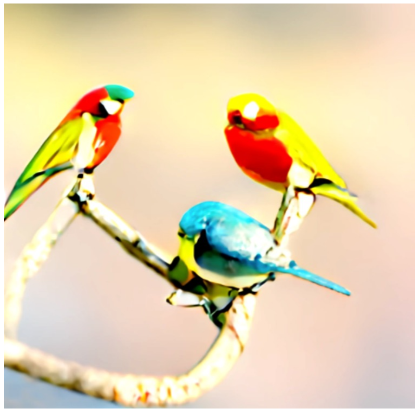
Overall Long-Term Prospects for NLDBD



In the long term will need more
than one isotope...
theory needed too!

Science Drivers in Neutrino Physics

These overlap many of our topical groups



Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

[redacted]

All of this discussion is in the context of the standard 3-flavor picture and testing that paradigm....

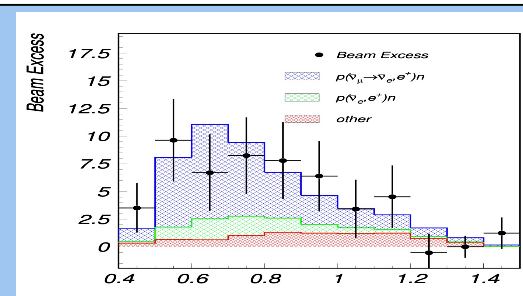
There are already some slightly uncomfortable data that **don't fit that paradigm**...

[redacted]

Status of attempts to resolve anomalies...

LSND @ LANL (~30 MeV, 30 m)

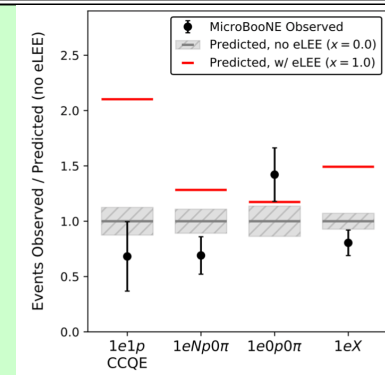
Unresolved... JSNS^2 will test



MiniBooNE @ FNAL ($\nu, \bar{\nu}$ ~1 GeV, 0.5 km)

Unresolved.... Results from MicrobooNE rule out specific electron/gamma final state explanations for LEE so far

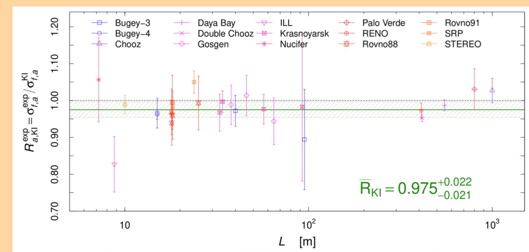
....more data from FNAL SBN program soon



"Reactor flux anomaly"

Resolved (probably?) with new input β-decay spectra from 235-U fission

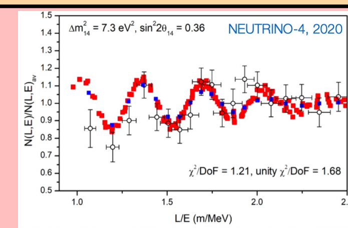
J. Kopp, Nu2022



"Reactor spectral anomaly"

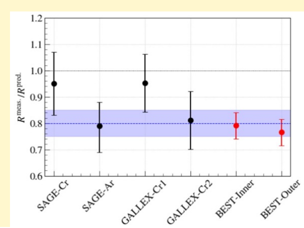
~Unresolved... new data disfavor.. more data coming...

PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....



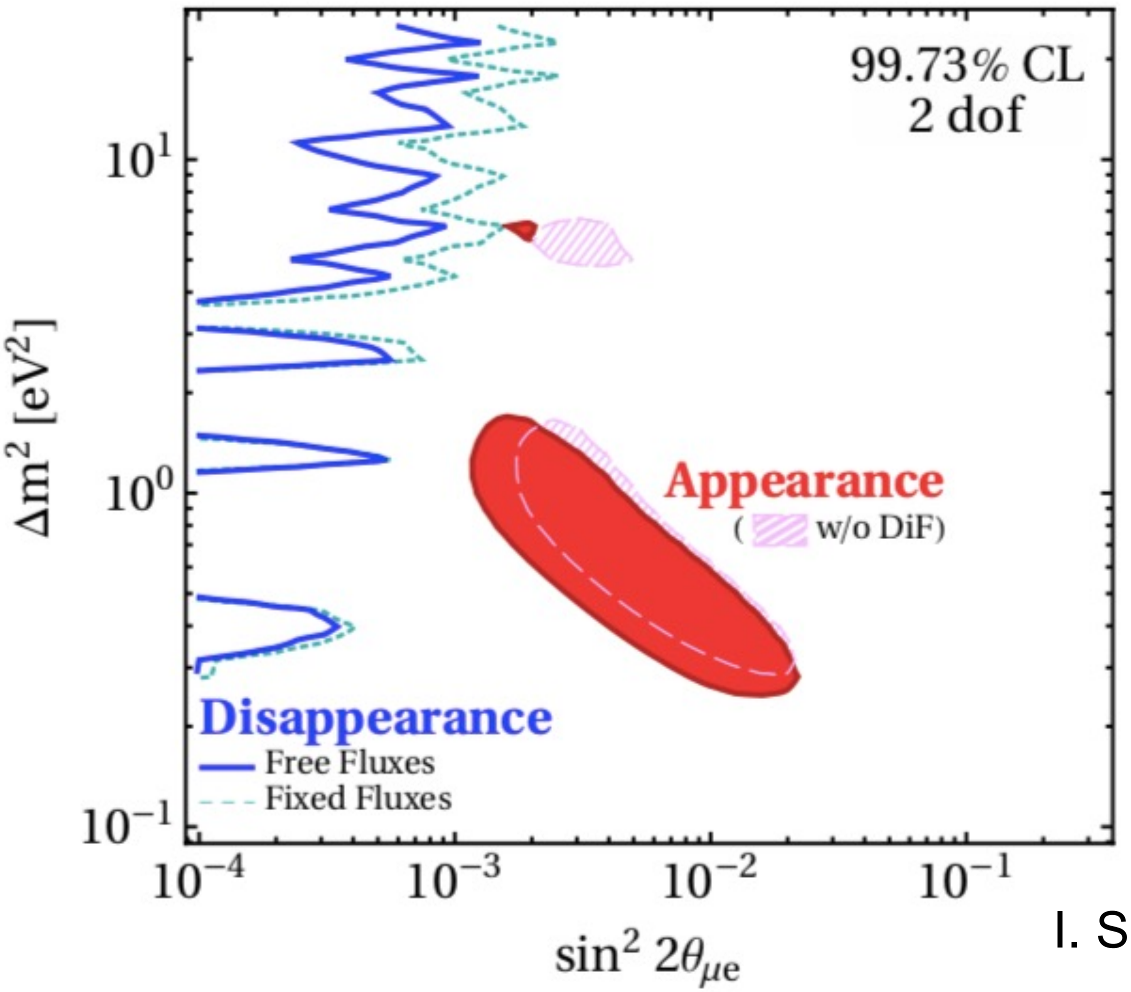
"Gallium anomaly"

Unresolved... new BEST results (5σ) confirm...no baseline dependence



[redacted]

Sterile oscillation fits to “all” the data are uncomfortable...



I. Soler

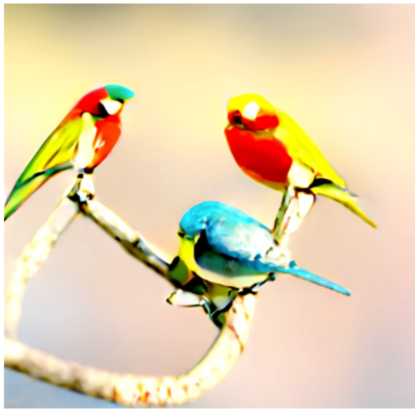
Appearance and disappearance data
are in fairly serious tension

M. Dentler et al. https://doi.org/10.1007/JHEP08(2018)010

[does not include PROSPECT, STEREO + other new data]

Science Drivers in Neutrino Physics

These overlap many of our topical groups



Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

Beyond the Standard Model in the Neutrino Frontier

This includes *both* BSM in the neutrino sector,
and BSM search opportunities in neutrino detectors

See colloquia by J. Kopp, Z. Tabrizi, M. Toups (+NF03 report)

dim-4: the Neutrino Portal

- ☑ one of the main portals to the dark sector
- ☑ superior sensitivity at future experiments (near & far detectors!)

dim-5: Neutrino Magnetic Moments

- ☑ starting probe TeV–scale new physics
- ☑ strong synergies between different searches

dim-6: Neutrinos in SMEFT

- ☑ model-independent formalism for high-scale new physics
- ☑ easy comparison between experiments

J. Kopp

- sterile neutrinos over wide range of masses
- neutrino decay
- PMNS non-unitarity
- anomalous ν magnetic moments
- non-standard ν interactions
- new physics in double beta decay

Very wide array of experimental approaches

[redacted]

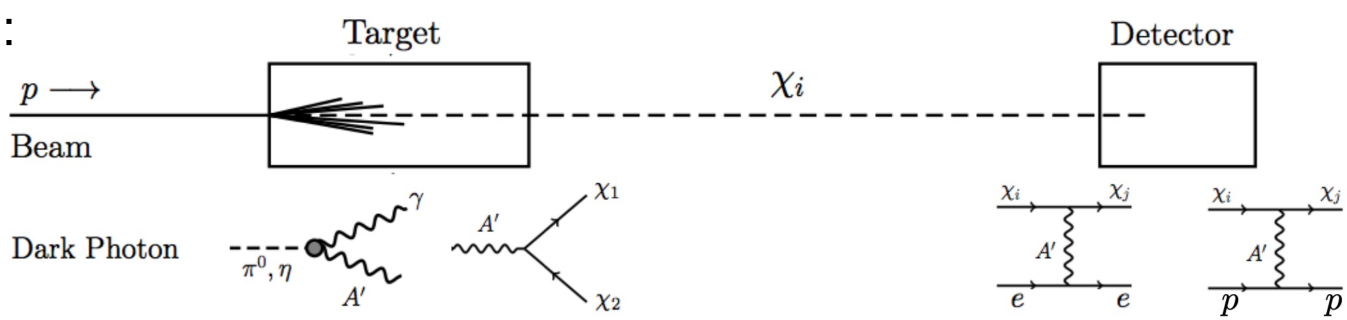
Note that in addition to BSM in the neutrino sector, there are **non-neutrino-sector BSM search opportunities in neutrino detectors**

See Pedro's talk

- Baryon number violation in large detectors
- Dark sector particle searches

  beams, natural sources, cosmogenic
  - Axion-like particles
  - Light DM
  - Light Z'

For example:



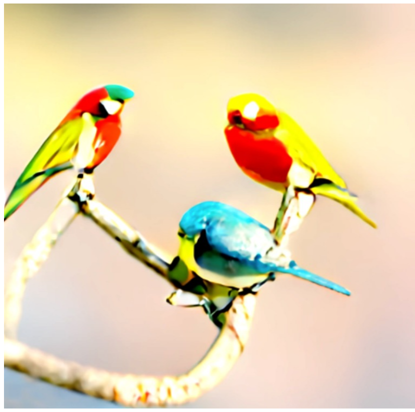
Matt Toups

- DUNE near detectors
- spallation neutron sources
- beam dumps
- LHC Forward Physics Facility
- neutrino factories
- ....

[redacted]

Science Drivers in Neutrino Physics

These overlap many of our topical groups



Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

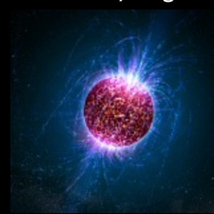
Multi-Messenger Astrophysics

Many, many sources

Supernovae + α

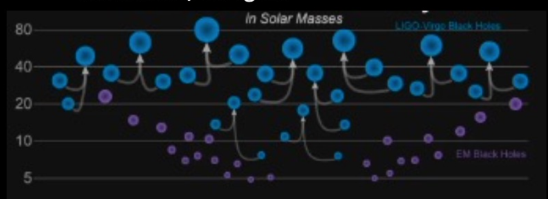
Supernova remnants

Neutron star, magnetar

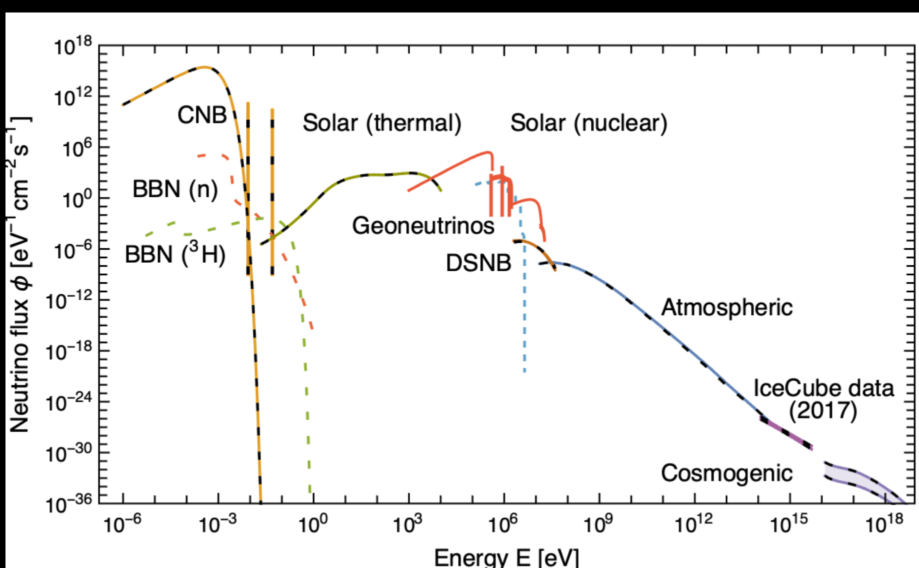


Dark matter
Primordial BH

Black hole / mergers



Supermassive black hole



Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF

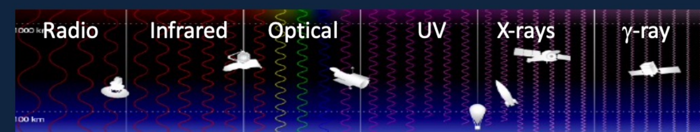
Many, many detectors

ν
SuperK + gadolinium
JUNO
DUNE
Hyper-Kamiokande
KM3NeT
IceCube-gen2
ARA

CR
LHAASO
PUEO
GRAND
TAMBO
POEMMA

GW
KAGRA
LIGO-India
LIGO Voyager
Cosmic Explorer
Einstein Telescope
LISA

γ



LAST
SKA

JWST

LSST
TMT
ELT

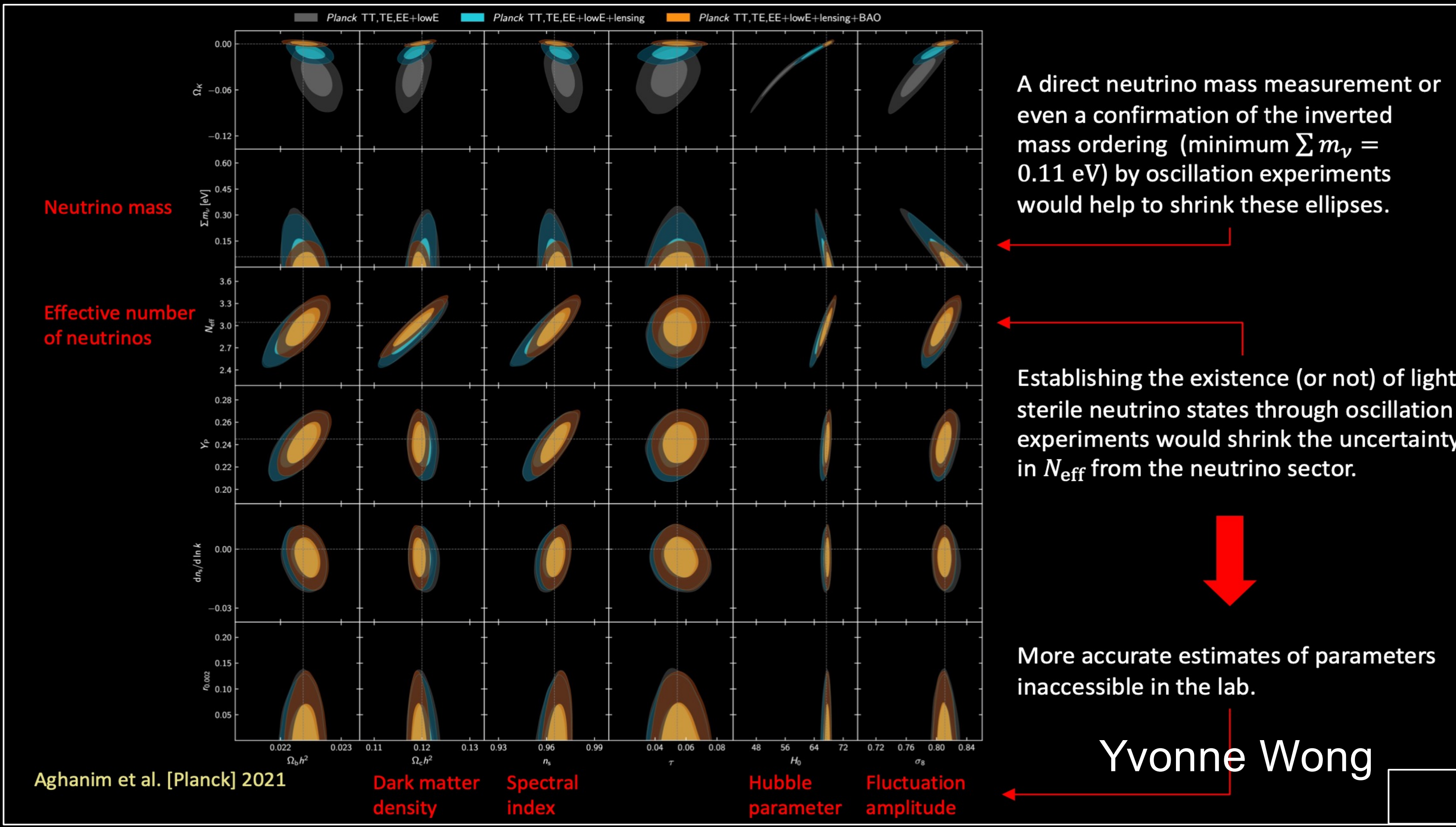
Athena

CTA
SWGO

Shunsaku Horiuchi

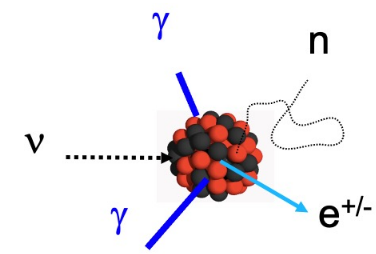
- Neutrinos are tools to understand the sources
- Natural neutrino sources are messengers of *physics*

Neutrinos and Cosmology



- Cosmological measurements tell us about ν properties
- Lab experiments help to constrain cosmological fits

And a final note: understanding of **neutrino interactions with matter** is very important, and connects to ~everything ... especially critical for oscillation physics



BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Astrophysics: supernova bursts, solar models

Tests of neutrino mixing model

Experiment	Source	Target
COHERENT	πDAR	Na, Ar, Ge, CsI,
Coherent CAPTAIN Mills	πDAR	Ar
JSNS^2	πDAR	
ESS	πDAR	
CHILLAX	Reactor	Ar
CONNIE	Reactor	Si
CONUS	Reactor	Ge
MINER	Reactor	Ge, Si
NEON	Reactor	Na
NUCLEUS	Reactor	
NUXE	Reactor	Xe
PALEOCCENE	Paleo	
Ricochet	Reactor	Ge, Zn
RED-100	Reactor	Xe
NuGen	Reactor	
SBC	Reactor	Ar
TEXONO	Reactor	Ge
NEWSG	Reactor	H, He, C, Ne

Many experimental & theory efforts over many orders of magnitude of neutrino energy

Short baseline Neutrino Program:
MicroBooNE, SBND, ICARUS
sbn.fnal.gov/

ANNIE
annie
annie.fnal.gov/

NuSTORM

MINERvA
minerva.fnal.gov/

MINERvA

NINJA

NINJA

Recent: Phys. Rev. D 102, 072006

[redacted]

Kendall Mahn

NF Recommendations Distilled from Community Input

Leadership in HEP-wide strategic plan for **DEI and community engagement**

- Neutrinos have connections to practically all other sectors of particle physics as well as many adjacent disciplines, offering neutrino physicists the opportunity to be community leaders in issues of diversity, equity and inclusion (DEI). These opportunities must be embraced. **The Neutrino Frontier has a special responsibility to contribute to leadership for a cohesive, HEP-wide strategic plan for DEI and community engagement.**

[redacted]

NF Recommendations Distilled from Community Input

Support for **neutrino theory**

- Many questions in neutrino physics arise from theory and conversely neutrino experimental results raise many theory questions. A strong neutrino theory program is therefore essential to reap the full scientific benefit from the investment into new experimental facilities. Moreover, there is a significant amount of theory understanding required to correctly connect experimental observables and simulations with the underlying physics parameters. **Strong and continued support for neutrino theory is needed.**

[redacted]

NF Recommendations Distilled from Community Input

Completion of ***full scope*** **of DUNE** recommended by the last P5

- There has been tremendous progress on oscillation physics with the current experiments and the DUNE/LBNF program since the last P5. However, the primary questions about the three-flavor paradigm remain unanswered, and the motivations for answering them, and probing new physics beyond the three-flavor paradigm, are undiminished. **Completion of existing experiments and execution of DUNE in its full scope are critical for addressing the NF science drivers**. Both Phase I and Phase II are part of the original DUNE design endorsed by the last P5. DUNE Phase I will be built in the current decade and DUNE Phase II (two additional far detector (FD) modules, a more capable near detector (ND), and use of the 2.4 MW beam power from the FNAL accelerator upgrade) is the priority for the 2030s.

[redacted]

NF Recommendations Distilled from Community Input

Support of **R&D for DUNE Phase II**

- Existing technologies enable the original DUNE physics program for both Phase I and Phase II. However each piece of DUNE Phase II offers broader physics opportunities than originally envisioned. **To exploit these new opportunities, directed R&D needs to be supported.** These opportunities for DUNE Phase II should be explored with a process inclusive of the community at large.

A lot of excitement about ND and FD Phase II opportunities

[redacted]

NF Recommendations Distilled from Community Input

Breadth of program in physics, size, timescale, supported by a deliberate process

- Opportunities for advances in the neutrino sector are entwined with opportunities in many other sectors, spanning all of the Snowmass Frontiers and multiple scales of time, size and cost. **A future program with a healthy breadth and balance of physics topics, experiment sizes, and timescales, supported via a dedicated, deliberate, and ongoing funding process, is highly desirable.** This process should also provide opportunities to explore and eventually resolve existing and future neutrino-related anomalies and to develop instrumentation and new beam technologies that will have a broad impact across the field. Furthermore, connections between programs should be carefully curated to optimize science output.

[redacted]

NF Recommendations Distilled from Community Input

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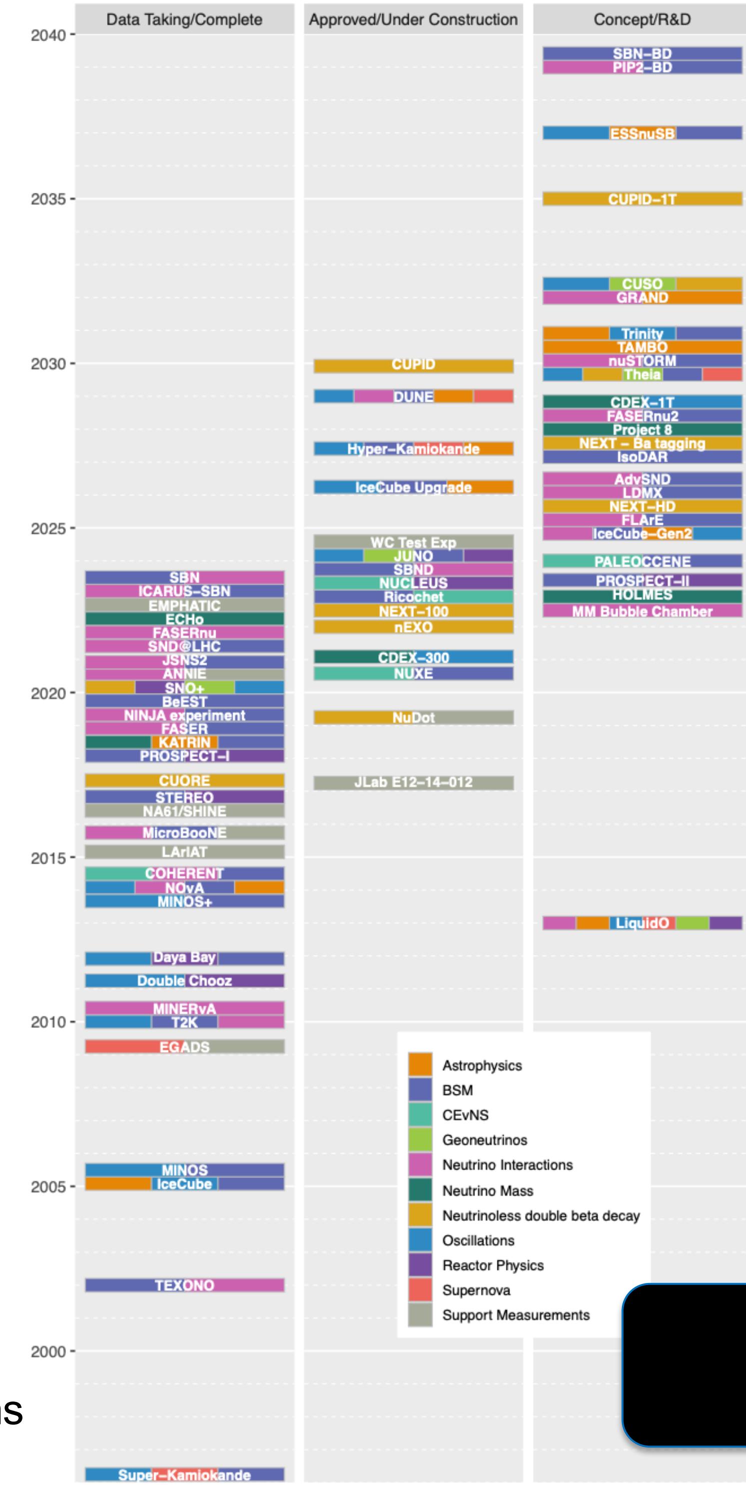
[redacted]

LOTS of NF-related projects,
with
great diversity of physics topics



During Snowmass we only collected rough timescale information...
for this talk,
I was charged with rough costing info

Info in this graphic from the collaborations

[redacted]

NF Projects in Coarse Cost Bins

Operating costs	Small (<$50M)		Medium ($50-200M)	Large (>$200M)
CUORE	ANNIE	AdVSND	CUPID-1T	DUNE
FASERnu	BeEST	CDEX-300	FPF	ESSnuSB
KATRIN	COHERENT	ECHo	NEXT w/Ba tag	IceCube-Gen2
Super-K	CUPID	GRAND	THEIA	nEXO
SBN	EMPHATIC	FLArE		nuSTORM
T2K	EOS-@-ORNL	Hyper-K	CUSO	LEGEND
	Hyper-K	HOLMES		
	IceCube Upgrade	JLab E12-14-012		
	IsoDAR	JUNO		
	JSNS2	LiquidO		
	LDMX	NUCLEUS		
	Modern Modular Bubble Chamber	PALEOCCENE		
	NEXT-CRAB	Ricochet		
	NINJA	TAMBO		
	NuDOT	Water Cherenkov Test Experiment		
	NUXE			
	PIP2-BD			
	Project 8			
	PROSPECT			
	SBC-CEvNS			
	SBN-BD			
	SNO+3%			
	Trinity			

- US-based costs.
- In grey: my guess for Snowmass submissions w/o collaboration-provided cost info [please correct!]
- Many subtleties not captured...

[redacted]

Comment

We have very many interests in common with the
NSAC Long Range Plan
Fundamental Symmetries, Neutrons and Neutrinos Working Group

https://indico.phy.ornl.gov/event/209/

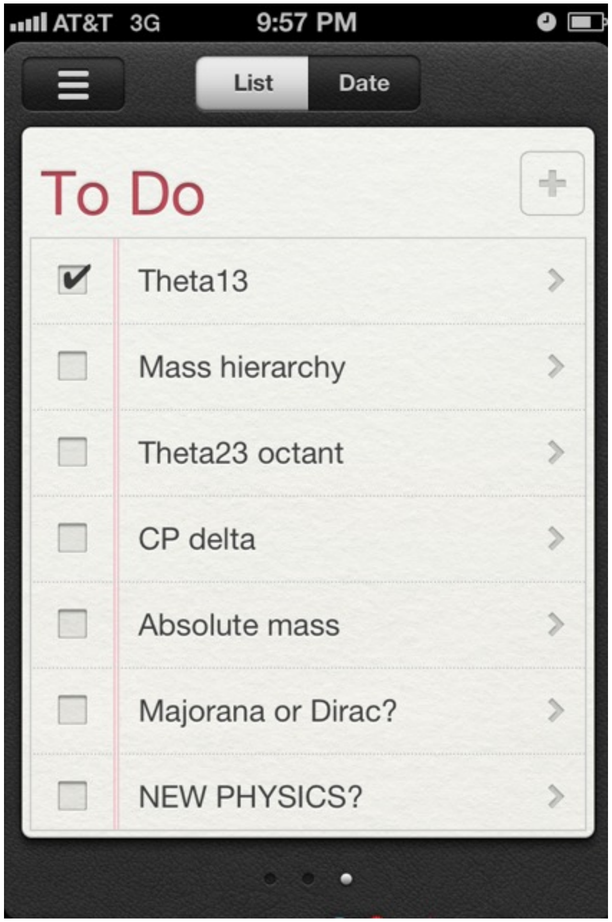
Snowmass NF Report: Searches for neutrinoless double beta decay investigate the Majorana or Dirac nature of the neutrino. The next generation of these experiments at the ton-scale is prepared to begin construction early in the coming P5 period. Completion of these experiments is a continuing focus of the neutrino physics community. Pursuing the physics associated with neutrino mass was a key Science Driver in the 2014 P5 report, and the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment was a top priority item in the 2015 Nuclear-Physics Long-Range Plan, a commitment that continues today under the stewardship of the Department of Energy Office of Nuclear Physics. A rich research and development program toward beyond-ton-scale sensitivities is underway. The envisioned experiments would be sensitive to a wide range of neutrino-physics phenomena, and the technologies under development may have broad applications in particle physics and beyond.

- neutrinoless double beta decay
- absolute mass kinematic experiments
- neutrino interactions
- other BSM, BNV, ...
- instrumentation

[redacted]

Overall Summary

Huge progress in understanding of neutrinos over the last 20 years, **but still many outstanding questions**



My IPhone from 11.5 years ago!*

[redacted]

*I have never found a good to-do list app...

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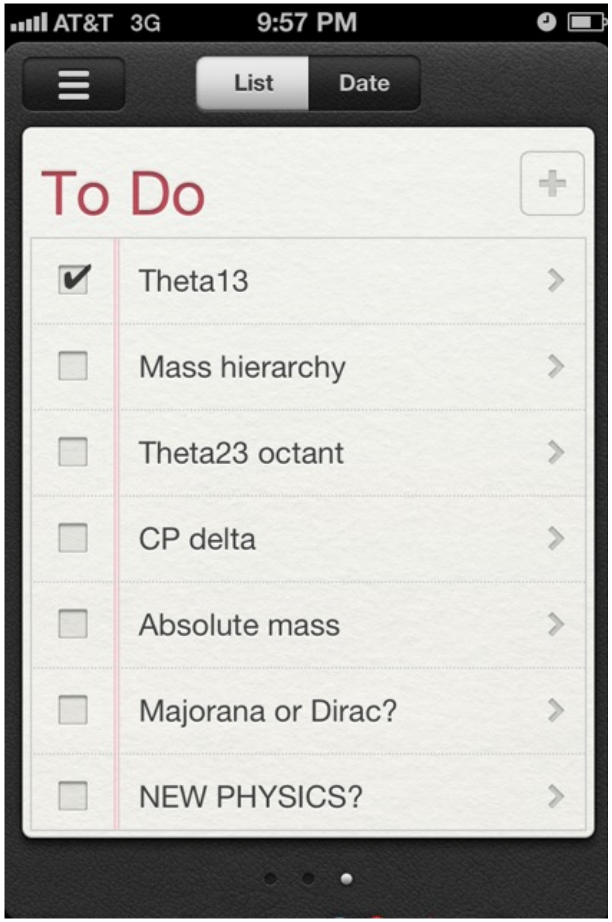

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[redacted]

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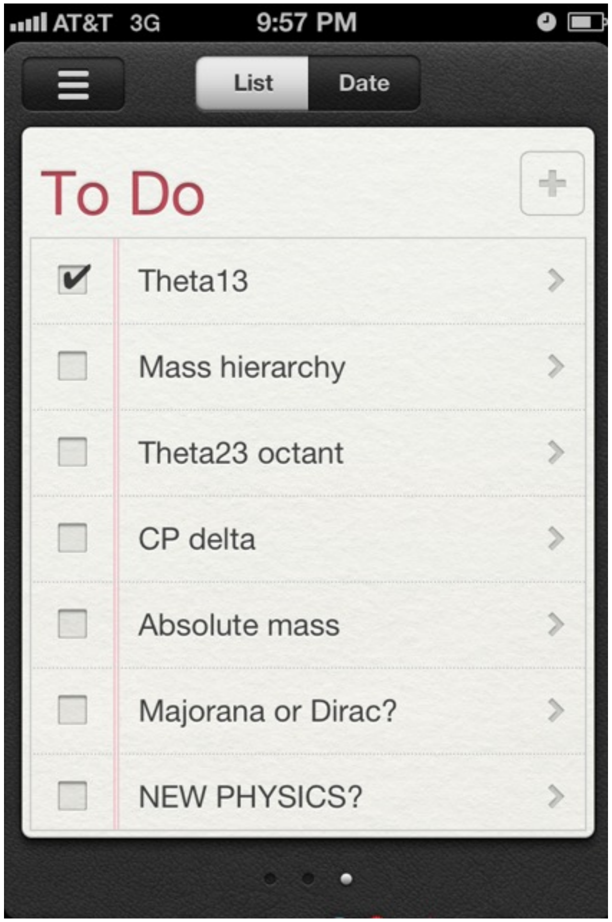

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More from KATRIN/P8 to come!

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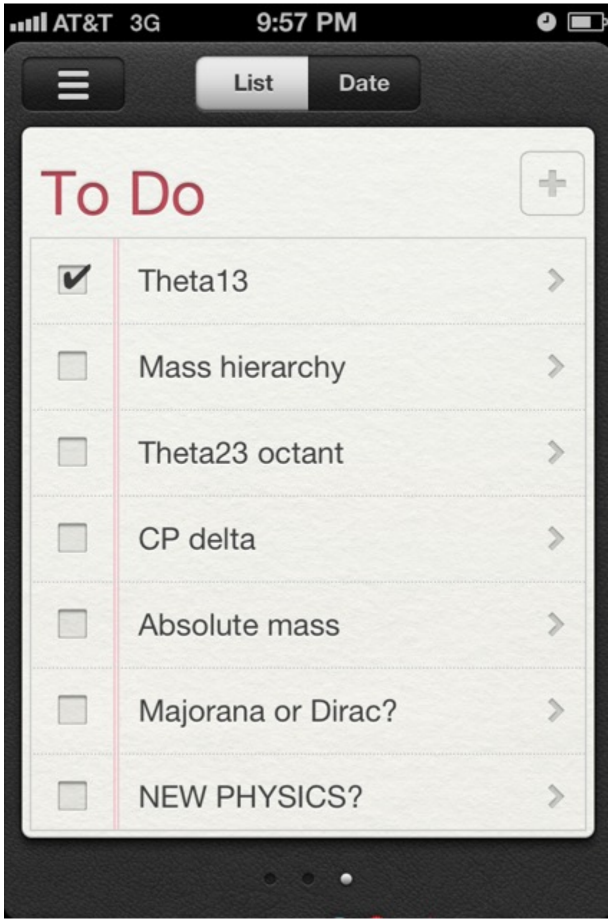

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Tonne-scale NLDBD program

[redacted]

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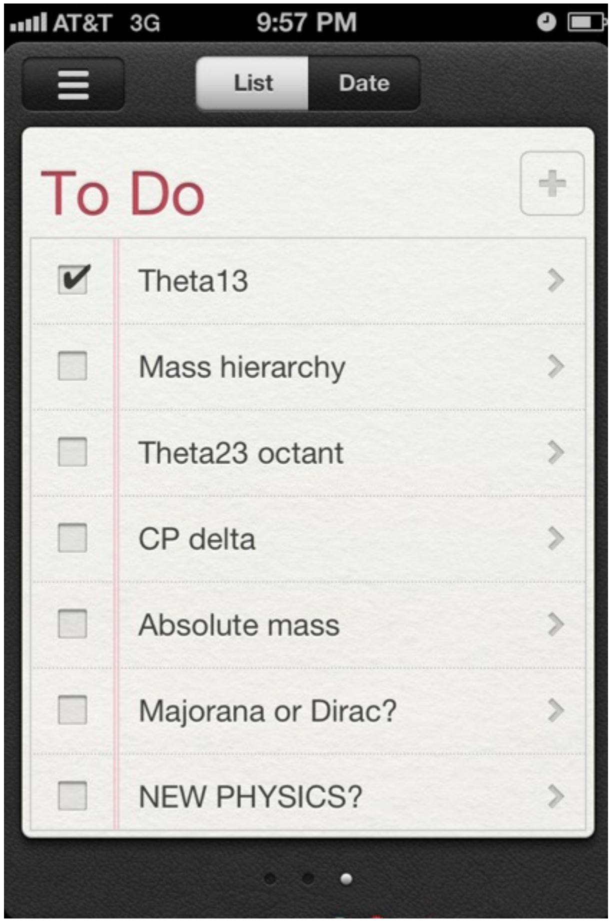

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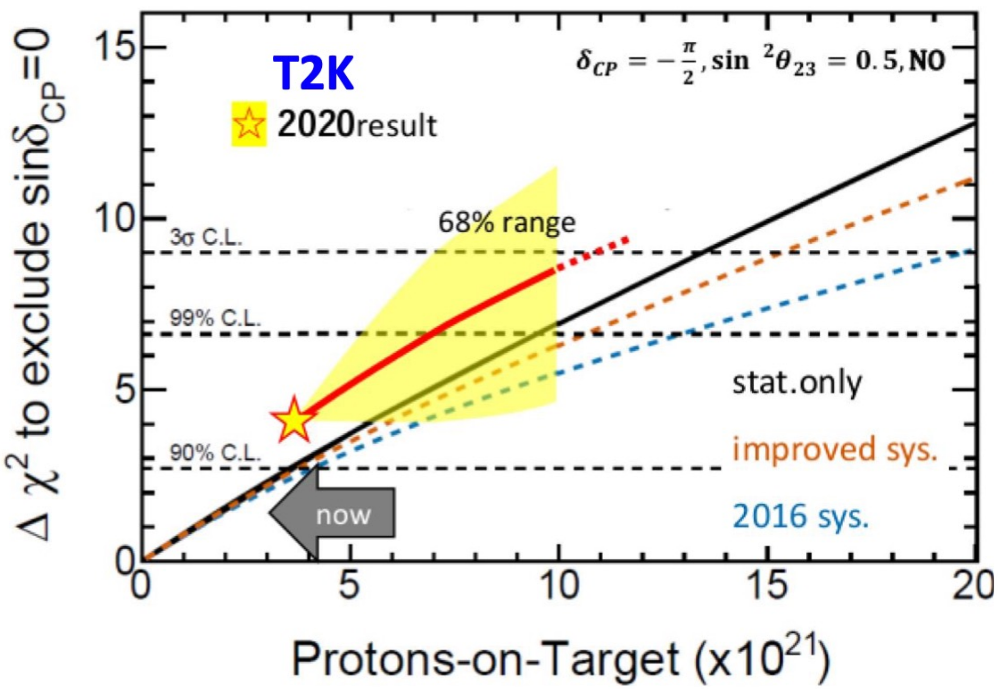
Tonne-scale NLDBD program

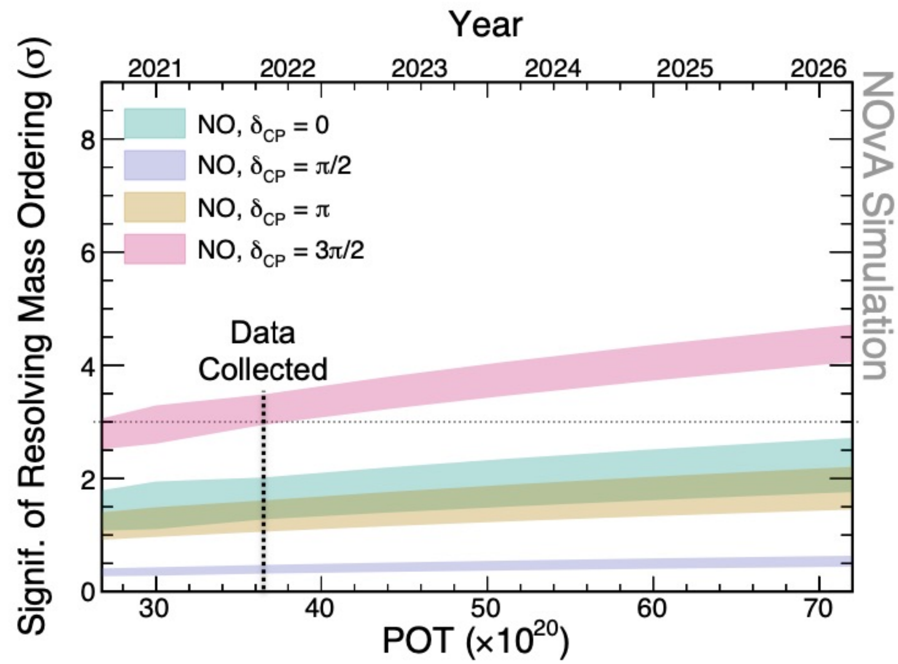
We must keep pushing on the paradigm and searching broadly for BSM

[redacted]

Extras/Backups

Future Prospects for T2K and NOvA





J. Hartnell, Nu2022

- Beam upgrade to >1 MW by ~2026
- Expect 10e21 POT by ~2027

- Will more than double dataset
- 3σ for 30-40% of CP δ range

Joint T2K-NOvA analysis in the works

...current generation is statistics-limited, but some chance of 2-3σ on δ/MO in next ~ 5 years

The Interest is Intense !

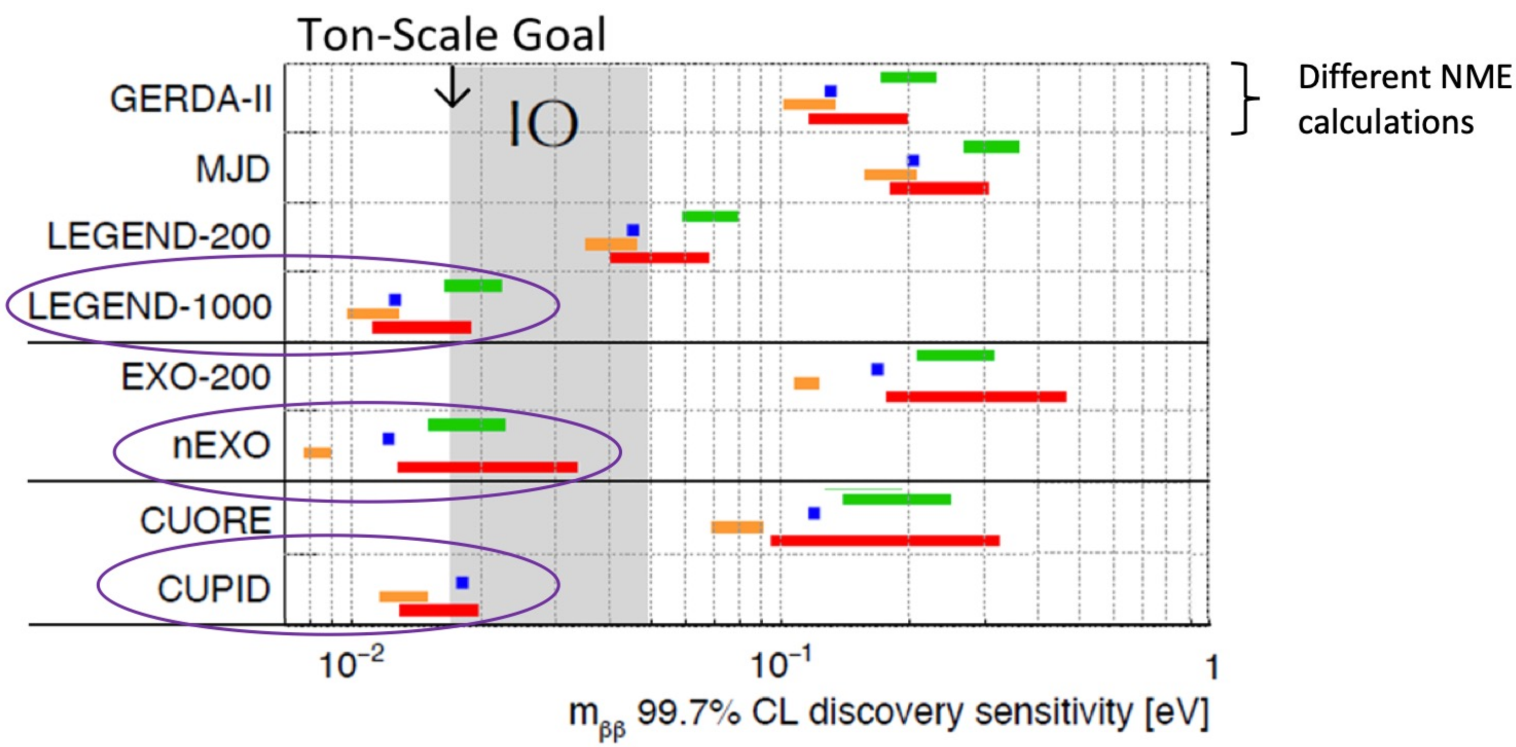
- The world summary of 0vbb from 1 kg to 1 kton
- From ongoing to proposed
- From "conventional" to "revolutionary"

But, we need to focus on 3 candidates ready for major funding with US leadership

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [84]	^{48}Ca	305 kg	$^{nat}CaF_2$ scint. crystals	Operating	Kamioka
CDEX-1 [85]	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300ν [85]	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0 [19]	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [86]	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
SuperNEMO [86]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
Selena [87]	^{82}Se		^{enr}Se, CMOS	Development	
IFC [88]	^{82}Se		ion drift SeF_6 TPC	Development	
CUPID-Mo [17]	^{100}Mo	4 kg	Li^{enr}MoO_4,scint. bolom.	Prototype	LNGS
AMoRE-I [89]	^{100}Mo	6 kg	^{40}Ca^{100}MoO_4 bolometers	Operation	YangYang
AMoRE-II [89]	^{100}Mo	200 kg	^{40}Ca^{100}MoO_4 bolometers	Construction	Yemilab
CROSS [90]	^{100}Mo	5 kg	$Li_2^{100}MoO_4$, surf. coat bolom.	Prototype	Canfranc
BINGO [91]	^{100}Mo		Li^{enr}MoO_4	Development	LNGS
CUPID [28]	^{100}Mo	450 kg	Li^{enr}MoO_4,scint. bolom.	Proposal	LNGS
China-Europe [92]	^{116}Cd		^{enr}$CdWO_4$ scint. crystals	Development	CJPL
COBRA-XDEM [93]	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [94]	^{116}Cd		^{nat}Cd CdTe. det.	Development	
TIN.TIN [95]	^{124}Sn		Tin bolometers	Development	INO
CUORE [10]	^{130}Te	1 ton	TeO_2 bolometers	Operating	LNGS
SNO+ [96]	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100 [97]	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [97]	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [98]	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	^{136}Xe	745 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	^{136}Xe		^{enr}Xe disolved in liq. scint.	Development	Kamioka
LZ [99]	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [79]	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [100]	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [101]	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [102]	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC [103]	^{136}Xe	kton	Xe-doped LR TPC	Development	
NuDot [104]	Various		Cherenkov and scint. in liq. scint.	Development	
Theia [105]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO [106]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [107]	Xe or Te		Slow Fluor Scint.	Development	

3σ discovery sensitivity in terms of $m_{\beta\beta}$.
(Smaller $m_{\beta\beta}$ indicate is better)

Note: In all cases, > ~10 fold improvements to below Inverted Ordering



D. Hertzog, FSNN Town Hall

Comparison of approaches and isotope characteristics

Experiment	CUPID	nEXO	LEGEND
Isotope	100-Mo	136-Xe	76-Ge
3 σ discovery $m_{\beta\beta}$ (10 yrs)	<18 meV	<18 meV	<18 meV
$Q_{\beta\beta}$	3034 keV	2458 keV	2039 keV
Res. Goal at $Q_{\beta\beta}$ (FWHM)	0.16% [5 keV]	1.9% [47 keV]	0.12% [2.4 keV]
Background index: Bkg in 1 FWHM in 10 T·yr:	10^{-4} /keV*kg*yr Net: ~2.2 cts in FWHM	(see footnote) Net: 3.2 cts in FWHM **	~10^{-5} /keV*kg*yr Net: 0.25 cts in FWHM
"Specific Phase Space" $H_{0\nu}$*	254.5	171.4	49.6
NME range per white paper	Ask Jon Engel	Ask Jon Engel	Ask Jon Engel
Isotope Mass (total mass)	240 kg (tot mass 450 kg)	4500 kg (tot mass 5000 kg)	975 kg (~1150 kg)
Basic technique	High res bolometers with heat and light to reject bkg	TPC with ionization and light to pinpoint decay coordinate	high-resolution Ge xtals; bkg reject by pulse and LAr veto
"Proud" feature	Large $Q_{\beta\beta}$ above natural γ bkgds; α rejection from dual readout; needs least mass to achieve goal; Cryo vessel	Combination of high exposure / self shielding + multivariate analysis to isolate signal from bkg.	Near-zero bkg demonstrated and best resolution; intermediate 200 kg phase started to demonstrate plans

- **Activity per unit mass**; See: Robertson *Mod.Phys.Lett.A* 28 (2013) 1350021
- ** nEXO provides a "background index" for an equivalently sensitive counting experiment in fiducial volume

D. Hertzog, FSNN Town Hall